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This paper describes a high-powered radio-frequency amplifier being developed for communications jamming and other applications in the HF band. It is intended to put out 10–100 kW over the 2–30 MHz band without tuning or filters. Its principle of operation is based on the current flowing through reverse-biased diodes due to the creation of electron-hole pairs by high-energy electrons passing through the junction regions. A set of 100–1000 diodes are combined in an array to make an amplifier with 10–100 kW of output power. This amplifier has the advantages of high power, small size, high gain, and high linearity.

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Electron-Bombarded Semiconductor Amplifier for High-Power, High-Frequency Output

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ABSTRACT A high-powered radio-frequency amplifier is being developed for communications jamming and other applications in the HF band. It is intended to put out 10–100 kW over the 2–30 MHz band without tuning or filters. Its principle of operation is based on the current flowing through reverse-biased diodes due to the creation of electron-hole pairs by high-energy electrons passing through the junction regions. A set of 100–1000 diodes are combined in an array to make an amplifier with 10–100 kW of output power. This amplifier has the advantages of high power, small size, high gain, and high linearity.

Introduction

A multiple-purpose wideband high-powered, HF-band amplifier using electron-bombarded semiconductor (EBS) technology is being developed at NRaD for communications jamming and other HF-band applications.

Before this project, extensive development work had been done at Watkins-Johnson, Co., Tektronics, and other companies under Navy contract, and since then the author has carried out experimental work on EBS amplifiers that used single diodes. The EBS diodes developed by these companies attained a high level of reliability (Ref. 1, 2). A project manager at NRaD asked the author if the EBS technology could be used to develop an amplifier for communications jamming that could meet the requirements of high power (10–100 kW), small size, wide instantaneous tuning bandwidth (2–30 MHz), high linearity, and low harmonics. The author realized that an amplifier using an array of EBS diodes had characteristics that would make it very well suited to meeting the requirements for a comunications jamming transmitter.

These expected advantages are its small size relative to its high power, high gain, wide bandwidth and high linearity. These advantages are discussed in a later section.

Several technical challenges must be faced in the development of an EBS amplifier. The first of these is its mechanical design. This includes the design of the housing, which needs to be compact, dissipate several kilowatts of heat, and maintain a vacuum. The mechanical design also includes the precise machining of the control grid and the precise mounting of the cathode and control gird.

Another technical challenge is to mount the diodes to the outer wall in a way that will provide electrical insulation while being able to carry off the heat that the diodes produce.

A third challenge is to develop failure protection for the diodes. The principal way to achieve this is through the conservative operation of the diodes, i.e., operation well within their power and voltage limitations. Protection is also achieved through connecting the diodes in series–parallel combinations that will allow failed diodes to be automatically bypassed, and through mounting the diodes with thin-wire filaments that can operate as fuses.

A fourth technical challenge is presented by the coupling from the amplifier to the antenna. The diodes can be connected in a variety of series–parallel combinations to match a wide range of impedances. This will aid in the impedance matching from the amplifier to the antenna.

A fifth challenge is posed by arcing inside the amplifier. The cathode and grid need to be mounted on a support structure that is able to hold off 15 kV. One advantage of an EBS amplifier over conventional tubes is that its high-voltage power supply only needs to put out a few milliamperes of current. The result of this limited current is that arcing in an EBS amplifier may cause the operation of the device to be interrupted but will not damage or destroy the amplifier, as it can conventional tubes.

One other technical challenge in the development of an EBS amplifier is oscillations. These oscillations, which result from the high gain of the amplifier, can be controlled through the careful placement of the components, including the input and output cables.

Applications

The primary motivation for the development of this EBS amplifier is communications jamming, but it is well suited for several other HF-band applications. These applications include frequency hopping and spread-spectrum communications. Possible applications also include HF-band radars, such as surface wave over-the-horizon radars. The amplifier will be useful for many HF-band applications, although filtering of the output may be required for some of them.

Description and Operation

The basic component of an EBS amplifier is the EBS diode, which is shown in Fig. 1. This is a specially designed silicon P–N junction diode, which is very broad in diameter (200 mils) and shallow in depth (5000 Å). The top of the diode is covered with a very thin aluminum layer, 1000 Å thick, which forms a top contact. The basic principle of the amplification by the diodes is based on the creation of electron-hole pairs in their reverse-biased P–N junctions by high-energy electrons passing through their junction regions.

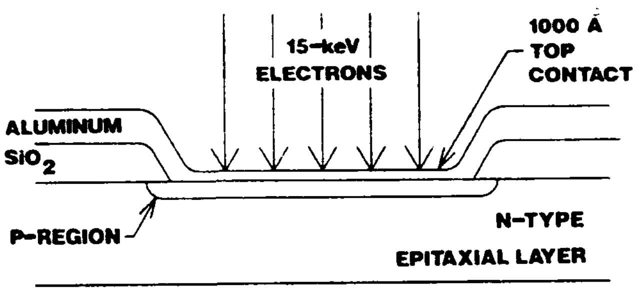

Figure 1. Cross section of diode.

In operation, the diode is reverse-biased at a potential of approximately 100 V and is bombarded with a beam of electrons that have an energy of 15 keV, as shown in Fig. 1. These electrons penetrate through the top metalization and pass through the P–N junction. Due to their high 15-keV energy, each electron creates approximately 3000 electron-hole pairs in the P–N junction. This results in an approximate 3000:1 current multiplication from the electron beam current that is incident on the diode, to the reverse current flowing through the diode (Ref. 3). The rate of creation of the electron-hole pairs in the P–N junctions is an exactly linear function of the current of the electron beam passing through it, so that the reverse diode current is a highly linear function of the incident beam current. The linearity of each diode will result in the entire diode array in the amplifier also functioning linearly.

Advantageous Diode Characteristics

Figure 2 shows plots of data recorded by the author. These plots show three characteristics of the diodes. The first is the high linearity of the output current as a function of the beam current. The second is the high current gain. The plots show that the ratio of the output current to the input current is approximately 3000:1. The third characteristic of the diode is its high-power output. The diode is shown to be able to switch an output current of approximately 22 A at an output voltage of 100 V. In these tests, the diodes were operated in a pulsed mode with a pulse rate of approximately 1 kHz and a pulse duration of approximately 10 μs.

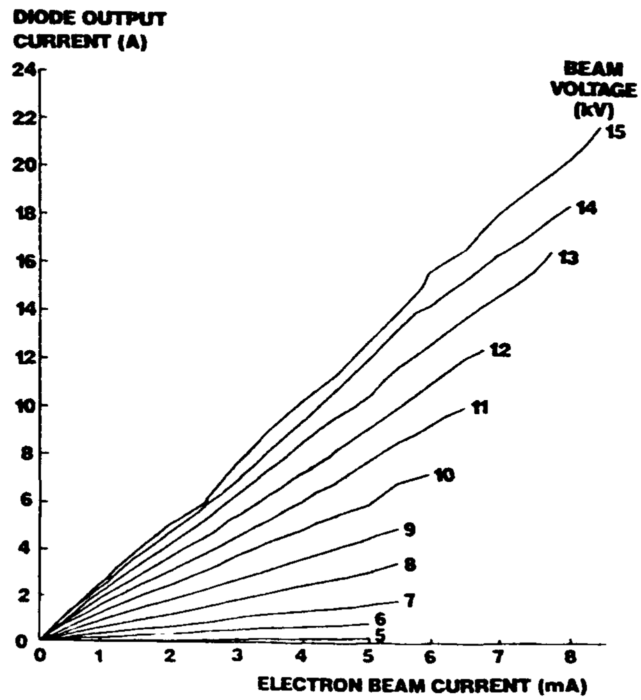

Figure 2. Diode output current as a function of electron beam current and voltage.

Amplifier Circuit

In the amplifier, 100–1000 reverse-biased diodes are connected in an array and bombarded by electrons to produce a large amount of signal amplification and power output.

The operation of the amplifier is shown in Fig. 3. The electrons for bombarding the diodes are emitted by the heated cathode (1). The cathode is at a potential of –15 kV, so that the electrons bombarding the array of diodes (2) have energies of 15 keV. The flow of electrons bombarding the diodes is modulated by the control grid (3). The control grid is also at a potential of –15 kV, with a small modulation voltage superimposed on the –15-kV potential. An inductive choke coil (4) is provided to prevent the RF output from passing into the power supply. A blocking capacitor (5) is provided to block the DC voltage of the power supply from passing into the output. The output of the amplifier is fed into the antenna sometimes through an impedance-matching circuit. Generally, two amplifiers will have their outputs connected in a push–pull configuration to improve the linearity and efficiency.

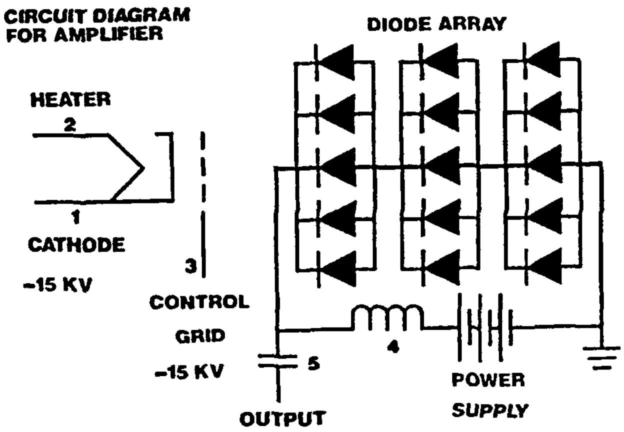

Figure 3. Circuit diagram for amplifier.

Mechanical Design

The mechanical design of the amplifier is illustrated in Fig. 4. The heated cathode (1) is mounted at the center of the amplifier. The control grid (2) surrounds the cathode. The ends of the cathode and control grid are mounted into aluminum oxide supports which are not shown in the figure. The spacing from the cathode to the control grid is a uniform 0.020 in. The cathode and grid must be positioned very accurately. This can be achieved through the use of precision laser machining of the aluminum oxide supports. The control grid is made from molybdenum or kovar tubing using laser machining. The diodes (3) are bonded on beryllium oxide ceramic substrates that are bonded to the housing (4), which is made of oxygen-free copper. The housing maintains a vacuum on the inside and conducts the heat dissipated by the diodes to the outside. The outside of the housing is cooled by water or forced air.

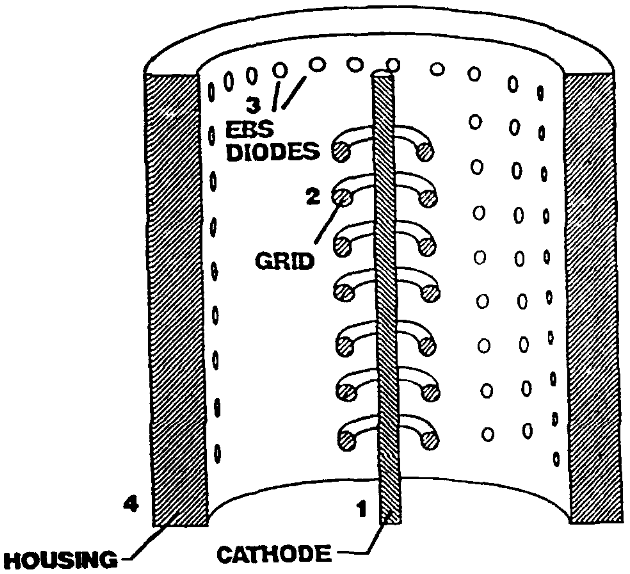

Figure 4. 100-kW EBS amplifier cross section diagram.

Figure 5 is an illustration of the mounting of the diodes onto the inside wall of the amplifier. A layer of beryllium oxide ceramic is used to separate the diodes from the wall. The beryllium oxide provides electrical isolation of the diodes from the outer wall, while providing excellent heat conduction to the wall. The beryllium oxide has copper directly bonded to both sides. A pattern is etched into the upper layer of copper using standard printed-circuit-board etching methods. The diodes are bonded to the copper using a gold germanium eutectic brazing alloy. The connection to the top contact of the diode is made using thin gold wires that are attached using wire bonding techniques. The bottom copper layer of the ceramic is attached to the wall of the housing using a second eutectic brazing alloy.

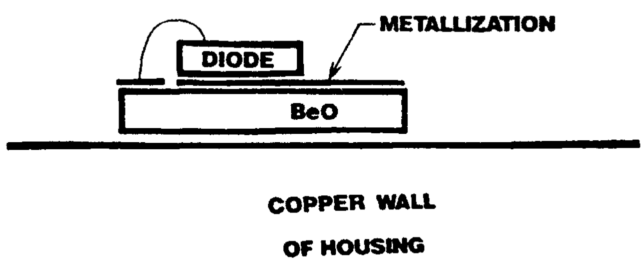

Figure 5. Mounting for individual diode.

Advantages and New Features of the EBS Amplifier

Amplifier devices have been built previously using electron-bombarded semiconductors, but they have had a single diode or a few diodes, and have been limited to less than 400 W. This amplifier will be the first to utilize approximately 100–1000 diodes connected in an array. This amplifier will also be the first to utilize some characteristics of EBS diodes that have not been utilized before. This will give the amplifier new capabilities: compactness, high gain, and high linearity.

One advantage of this planned amplifier over the previous approach is its small size relative to its high power. Each diode can conservatively handle 100 W of output power, so that approximately 100 diodes will be required for a 10-kW amplifier, and approximately 1000 diodes will be required for a 100-kW amplifier. Each diode will have a diameter of approximately 1/4 in., so that there will be approximately 10 diodes per square inch on the inside surface of the housing. For 10 or 100 kW of output power, the inside surface of the anode will be approximately 10 or 100 in^2, so that this amplifier will occupy a volume of less than 1 ft^3. This is a major advantage over the previous method for building a wideband communication jamming amplifier, which uses multiple solid-state output sections and fills several 19-inch racks.

Another advantage of this amplifier is its high gain due to the 3000:1 current gain of the diodes. This allows the amplifier to be directly driven by a relatively low-power driver stage, eliminating the need for a high-powered driver preamplifier.

An additional advantage of the amplifier is its high linearity resulting from the diode output current being a highly linear function of the incident electron beam current. It should be relatively easy to build a highly linear amplifier that can cover the 2–30 MHz frequency range with the harmonics suppressed more than 40 dB below the output signal without the need for using tuned circuits or filters in the output section.

The combination of these new features should make this amplifier significantly superior to previous amplifier devices.

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